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Analysis of intra-institutional research collaboration: a case of a Serbian faculty of sciences

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Abstract Current research information systems (CRISs) offer great opportunities for scientometric studies of institutional research outputs. However, many of these opportunities have not been explored in depth, especially for the analysis of intra-institutional research collaboration. In this paper, we propose a hybrid methodology to analyze research collaboration networks with an underlying institutional structure. The co-authorship network extracted from the institutional CRIS of the Faculty of Sciences, University of Novi Sad, Serbia, is analyzed using the proposed methodology. The obtained results show that the organizational structure of the institution has a profound impact on both inter- and intra-institutional research collaboration. Moreover, researchers involved in inter-department collaborations tend to be drastically more productive (by all considered productivity measures), collaborative (measured by the number of co-authorship relations) and institutionally important (in terms of the betweenness centrality in the co-authorship network) compared to those who collaborate only with colleagues from their own research departments. Finally, our results indicate that quantifying research productivity by the normal counting scheme and Serbian research competency index is biased towards researchers from physics and chemistry research departments.

Keywords intra-institutional research collaboration · co-authorship networks · network analysis · current research information systems · researcher evaluation

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1 Introduction

Research collaboration is one of the key social features of modern science (Milojević, 2010; Glänzel and Schubert, 2005). It can be observed and studied at many levels: individual, institutional, national, disciplinary, etc. At all of these levels, major research questions are how research collaboration is structured, how it evolves, and how it is related to research productivity and the impact of multi-authored publications. As emphasized by Glänzel and Schubert (2005), research collaboration can be reliably captured by so called *co-authorship networks* since co-authorship is one of the most concrete and well documented manifestations of collaboration in science. The nodes in a co-authorship network represent researchers. Two researchers are connected by an undirected link if they co-authored at least one publication together. Additionally, weights can be assigned to links in order to express the strength of research collaboration.

Empirical studies investigating scientific collaboration date back to the 1960s. A more recent resurgence of interest in the field was sparked by the observation of the small-world and scale-free phenomena in various types of complex, real-world networks (Watts and Strogatz, 1998; Barabasi and Albert, 1999). Mark Newman in his seminal papers (Newman, 2001a,b) proposed a general methodological framework based on metrics and methods of complex network theory to analyze scientific collaboration networks. Following his framework researchers investigated the structure and evolution of a variety of co-authorship networks observing properties such as:

- heavy-tailed distributions of node centrality metrics,
- network evolution governed by the preferential attachment principle,
- the small-world property additionally emphasized by shrinking diameters,
- an evolutionary increase of average node degree and densification laws,
- the funneling effect,
- the existence of a giant connected component,
- assortative mixing patterns, and
- a high degree of local clustering and community structures at the mesoscopic level (Savić, 2015).

A vast majority of existing studies on co-authorship networks are mainly oriented towards inter-institutional, international, national and collaboration within scientific disciplines (Kumar, 2015; Savić, 2015). To the contrary, empirical studies of intra-institutional research collaboration networks are exceptionally rare. In a recent comprehensive literature review made by Kumar (2015) only two such studies are present: (1) the study by Newman (2004a) who investigated the application of the Girvan-Newman community detection method on the co-authorship network of the Santa Fe institute, and (2) the study by Pepe and Rodriguez (2010) who investigated mixing patterns in the co-authorship network of the CENS research center. To the best of our knowledge, there are three more studies dealing with the analysis of intra-institutional co-authorship networks: Bellanca (2009), De Stefano et al (2011) and Birnholtz et al (2013) analyzed co-authorship networks of University of York (UK), University of Salerno (Italy), and two campuses of Cornell University (USA), respectively.

Current research information systems (CRISs) offer great opportunities for scientometric studies at the intra-institutional and intra-national levels. For example, van Leeuwen et al (2016) exploited CRIS data to perform bibliographic analysis of research output of a Dutch university. Perc (2010) analyzed the structure and evolution of the co-authorship network encompassing Slovenian researchers which was formed from data stored in SICRIS (a national CRIS system for Slovenia). We are not aware of any study of intra-institutional research collaboration based on co-authorship networks constructed from CRIS-based data sources.

In this paper, we present a hybrid methodology for the analysis of intra-institutional co-authorship networks extracted from CRIS databases. This means that nodes in an analyzed network represent researchers who are institutionally organized into research departments within the corresponding institution. The proposed methodology can be applied on any *enriched intra-institutional co-authorship network*, i.e. intra-institutional co-authorship networks whose nodes and links are enriched with both domain-independent metrics (metrics used in analysis of complex and social networks which are directly computed from the network) and domain-dependent metrics (e.g. metrics of researcher productivity and competency, collaboration strength and timespan).

Using the proposed methodology, we analyze the intra-institutional co-authorship network of the Faculty of Sciences, University of Novi Sad, Serbia (from this point on we use the term "FS-UNS" to denote this particular faculty). The primary goal of the analysis is to investigate how the organizational structure of the institution affects research collaboration and productivity. The network is constructed from the institutional CRIS called CRIS-UNS [1]. We exploited all benefits that the implementation of CRIS-UNS provides: (1) no name disambiguation problems, and (2) the categorization of publications according to the rule book prescribed by the Serbian Ministry of Science.

The rest of the paper is structured as follows. Section 2 presents our methodology to analyze intra-institutional research collaboration networks. Researcher evaluation metrics used in our case study are briefly explained in Section 3. Section 4 describes the background of our case study. The obtained results are presented and discussed in Section 5. Finally, the last section concludes the paper.

2 Methodology

Our methodology for the analysis of intra-institutional co-authorship networks is based on the combination of (1) domain-independent metrics and methods used in analysis of complex networks, (2) domain-dependent metrics of

[1] http://www.cris.uns.ac.rs/

researcher productivity and collaboration strength, and (3) non-parametric statistical tests applied to the sets of metric values of independent groups of nodes/links. An intra-institutional co-authorship network is an undirected and weighted graph where link weights express the strength of research collaboration. The following schemes are commonly used to assign weights to co-authorship links:

- *Straight scheme* where two researchers are connected by a link of weight w if they coauthored exactly w different research papers (Batagelj and Cerinšek, 2013).
- *The Salton scheme* which is a normalized variant of the previous scheme, i.e the weight of a link is in the interval $(0, 1]$ and proportional to the number of joint publications (Lu and Feng, 2009), and
- *The Newman scheme* which takes into account the total number of authors in multi-authored publications (Newman, 2004b). In our study of the FS-UNS co-authorship network this scheme is used to determine link weights.

We assume that nodes in the analyzed co-authorship network are enriched with metrics quantifying productivity, collaboration and institutional importance of corresponding researchers. The same applies for links that are enriched with their importance within the network and timespan (the number of years that passed from the first to the last joint publication of authors connected by the link). Considering the standard organizational structure of research institutions, we assume that each researcher belong to exactly one research department within the institution. Consequently, we distinguish between two types of links:

1. *intra-department links* – co-authorship links connecting researchers belonging to the same research department, and
2. *inter-department links* – co-authorship links connecting researchers from different departments.

The methodology proposed in this paper consists of four general steps:

1. The identification and analysis of connected components in the network in order to evaluate the overall collaborative cohesiveness of the institution,
2. The analysis of collaborative cohesiveness of research departments based on graph clustering evaluation metrics,
3. The analysis of inter-department links in order to evaluate research collaboration between departments, as well as to detect differences between researchers involved in inter-department collaborations and researchers whose collaboration is bounded to their own departments, and
4. The comparison of departments relying on researcher evaluation metrics in order to detect similarities and differences in their productivity, collaboration and institutional importance.

A connected component of an undirected network is a maximal set of mutually reachable nodes, i.e. there is a path connecting each two nodes in the component. Connected components can be detected using classical graph traversal algorithms (Breadth First Search or Depth First Search). We distinguish between two types of connected components: isolated nodes and non-trivial connected components of research collaboration.

Definition 1 (Isolated node) A node in an intra-institutional co-authorship network is called isolated if it is not connected to any other node in the network, i.e. its degree centrality is equal to zero.

Definition 2 (Non-trivial component) A connected component in an intra-institutional co-authorship network is considered non-trivial if it encompasses more than one node.

Isolated nodes represent researchers who have never collaborated with their institutional colleagues. Therefore, a large number of isolated nodes in the network indicates a poorly connected institutional research community. The size of the largest non-trivial connected component is also an indicator of the overall collaborative cohesiveness of the institution.

Definition 3 (Giant component) A non-trivial connected component is considered giant if it encompasses a vast majority of nodes in the network.

The existence of giant connected components is one of the main features of co-authorship networks (Newman, 2001c,a,b, 2004b; Barabasi et al, 2002; Bettencourt et al, 2009; Perc, 2010). The absence of a giant connected component in an intra-institutional research collaboration network implies a poorly cohesive institutional community of researchers, further indicating that the institution is still in an early phase of its scientific development. The structure of connected components can be characterized by various metrics proposed under the framework of complex network theory such as the clustering coefficient, the characteristic path length and the assortativity index (Boccaletti et al, 2006; Savić et al, 2014).

Another common characteristic of co-authorship networks is the existence of community or cluster structure (Girvan and Newman, 2002; Newman, 2004a; Leskovec et al, 2009; Savić et al, 2015) where clusters are viewed as subsets of nodes that are more densely internally connected than with the rest of the network. In recent times significant research efforts have been devoted to the development of community detection methods (Fortunato, 2010; Chen et al, 2015) and graph clustering evaluation (GCE) metrics which quantify the quality of detected communities (Leskovec et al, 2010). For intra-institutional co-authorship networks there is also another notion of communities that is determined by the organizational structure of research institutions. Such institutionally determined research communities are not necessarily strong clusters in co-authorship networks. Namely, if a research department exhibits a low degree of collaborative cohesiveness then the researchers belonging to the department form a poor cluster in the co-authorship network. Therefore, we adopted three GCE metrics to quantify collaborative cohesiveness of research departments: internal density (ID), weighted conductance (WC) and weighted Flake degree fraction (WFDF) (Leskovec et al, 2010).

To formally define aforementioned cohesiveness metrics we will assume that

– G denotes an intra-institutional co-authorship network,
– D an arbitrary research department (a subset of nodes of G),
– r an arbitrary researcher within D, and
– $G[D]$ the sub-network of G induced by D, i.e. $G[D]$ encompasses researchers from D and all intra-department links between them.

The density of a network is the number of links in the network divided by the maximal number of links that the nodes can form.

Definition 4 (Internal density) The internal density of research department D is the density of $G[D]$, i.e. $\text{ID}(D) = 2l/n(n-1)$, where n and l are the number of nodes and links in $G[D]$, respectively.

Higher values of ID indicate more cohesive departments. If $\text{ID}(D) = 0$ then D consists of isolated nodes (no research collaboration within D). On the opposite side, $\text{ID}(D) = 1$ implies that D is a clique which means that each two researchers from D co-authored at least one paper together.

The strength of research collaboration of researcher r with other researchers within the institution can be estimated by its weighted degree in the co-authorship network. Moreover, we can distinguish between weighted intra-department and weighted inter-department degrees which reflect the total strength of research collaboration of r with researchers from his/her department and researchers from other departments, respectively.

Definition 5 (Weighted intra-department degree) The weighted intra-department degree of researcher r, denoted by $w^{\text{intra}}(r)$, is the sum of weights of intra-department links incident to r.

Definition 6 (Weighted inter-department degree) The weighted inter-department degree of researcher r, denoted by $w^{\text{inter}}(r)$, is the sum of weights of inter-department links incident to r.

Definition 7 (Weighted degree) The weighted degree of researcher r, denoted by $w(r)$, is the sum of weights of all co-authorship links incident to r, i.e. $w(r) = w^{\text{intra}}(r) + w^{\text{inter}}(r)$.

Definition 8 (Total weight) Let L' be a subset links in the network. The total weight of L' is the sum of weights of all links contained in L'.

Definition 9 (Weighted conductance) The weighted conductance of D is equal to the total weight of inter-department links incident to nodes in D normalized by the total weighted degree of nodes in D, i.e.

$$\begin{aligned}\text{WC}(D) &= \sum_{r \in D} w^{\text{inter}}(r) \Bigg/ \sum_{r \in D} w(r) \\ &= \sum_{r \in D} w^{\text{inter}}(r) \Bigg/ \left(\sum_{r \in D} w^{\text{inter}}(r) + \sum_{r \in D} w^{\text{intra}}(r) \right).\end{aligned}$$

Definition 10 (Weighted Flake degree fraction) The weighted Flake degree fraction of D is the fraction of researchers in D whose weighted intra-department degree is strictly higher than weighted inter-department degree, i.e.

$$\text{WFDF}(D) = \big|\{r : r \in D \wedge w^{\text{intra}}(r) > w^{\text{inter}}(r)\}\big| \ / \ \big|D\big|.$$

The main difference between ID and the other two GCE metrics (WC and WFDF) is that ID takes into account only intra-department links, while WC and WFDF consider both intra-department and inter-department links. The main advantage of WC and WFDF compared to all other known GCE metrics is that they enable the classification of research departments according to the Radicchi notion of communities in complex networks (Radicchi et al, 2004). The Radicchi notion of communities extends the concept of highly cohesive subgraphs known as LS-sets, and nowadays it is one of widely used standards for the evaluation of community detection techniques (Fortunato, 2010). Department D can be viewed as a Radicchi strong cluster of researchers if each researcher in D has established stronger collaboration within D than with researchers from other departments, i.e.

$$\begin{aligned} \text{D is a Radicchi strong cluster } &\iff (\forall r \in D)\, w^{\text{intra}}(r) > w^{\text{inter}}(r) \\ &\iff \text{WFDF}(D) = 1.0 \end{aligned}$$

On the other hand, D is a Radicchi weak cluster if the total strength of intra-department collaboration within D is higher than the total strength of collaborations between D and all other departments, i.e.

$$\begin{aligned} \text{D is a Radicchi weak cluster } &\iff \sum_{r \in D} w^{\text{intra}}(r) > \sum_{r \in D} w^{\text{inter}}(r) \\ &\iff \text{WC}(D) < 0.5 \end{aligned}$$

Each Radicchi strong cluster is also Radicchi weak, while the converse is not necessarily true.

The previously defined GCE metrics will be illustrated on the hypothetical intra-institutional research collaboration network shown in Figure 1. The network depicts a small research organization that consists of 10 researchers (denoted by letters from A to J) which are institutionally organized into three research departments denoted by P, Q and R. It can be observed that the network contains 9 intra-department and 5 inter-department links. There are 4 links incident to researcher A: 2 intra-department links ($A \leftrightarrow B$ and $A \leftrightarrow C$) and 2 inter-department links ($A \leftrightarrow D$ and $A \leftrightarrow F$). The weighted intra-department degree of A is $w^{\text{intra}}(A) = w(A \leftrightarrow B) + w(A \leftrightarrow C) = 9 + 3 = 12$, while its weighted inter-department degree is $w^{\text{inter}}(A) = w(A \leftrightarrow D) + w(A \leftrightarrow F) = 6 + 2 = 8$. Therefore, we can conclude that A has established stronger collaboration with researchers from its own department than with researchers from other departments.

Department P is a clique: every two researchers from P have established research collaboration. Therefore, the internal density of P is equal to 1. P

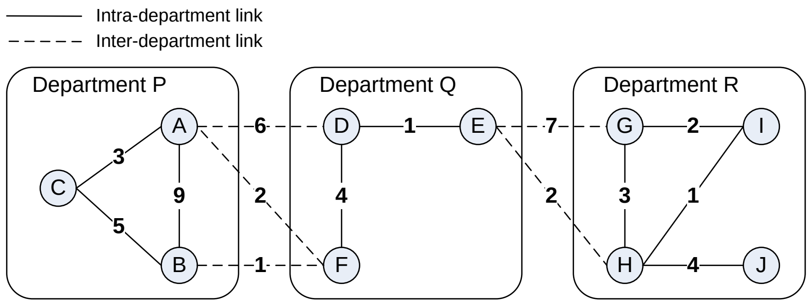

Fig. 1 A hypothetical intra-institutional research collaboration network of an institution with three research departments.

is also a Radicchi strong cluster: for each researcher $p \in P$ we have that $w^{\text{intra}}(p) > w^{\text{inter}}(p)$ ($w^{\text{intra}}(A) = 12$, $w^{\text{inter}}(A) = 8$, $w^{\text{intra}}(B) = 14$, $w^{\text{inter}}(B) = 1$, $w^{\text{intra}}(C) = 8$, $w^{\text{inter}}(C) = 0$). Department R is not a Radicchi strong cluster: $\text{WFDF}(R) = 3/4$ since G is the only researcher from R whose weighted intra-department degree is lower than the weighted inter-department degree. However, this department is a Raddichi weak cluster:

$$\sum_{r \in R} w^{\text{inter}}(r) = 9, \sum_{r \in R} w^{\text{intra}}(r) = 20 \Rightarrow \text{WC}(R) = 9/29 < 0.5$$

Department Q is neither Raddichi strong nor Radicchi weak: $\text{WFDF}(Q) = 1/3$ (researchers D and E have lower weighted intra-department than weighted inter-department degrees) and $\text{WC}(Q) = 18/28 > 0.5$.

Our example clearly shows that internal density cannot fully reflect the cohesiveness of departmental research collaboration. Namely, departments Q and R, being drastically different considering their cohesiveness, have the same value of internal density ($\text{ID}(Q) = \text{ID}(R) = 2/3$). Relying on internal density we can detect whether researchers from some department form a clique (the most cohesive research collaboration structure) and measure the degree to which organizational units deviate from being cliques, but this metric cannot separate strong from poor research collaboration clusters. On the other hand, WC and WFDF are complementary measures of collaborative cohesiveness:

– Using WFDF it can be checked whether research departments possess a strong degree of collaborative cohesiveness (i.e. Raddichi strong clusters), but this measure cannot separate poorly (non Radicchi weak) from moderately cohesive (Radicchi weak) research departments.
– WC can indicate poorly cohesive research departments, but it cannot separate strongly from moderately cohesive research departments.

To evaluate inter-department collaborations we analyze the structure of a departmental collaboration network, i.e. the network of research collaboration between research departments within the institution. The departmental network is constructed from the co-authorship network by the following rules:

1. The nodes of the departmental network represent research departments of the institution.
2. Two departments A and B are connected by an undirected, weighted link if at least one researcher from A has collaborated with at least one researcher from B.
3. The weight of the link connecting A and B is equal to the sum of weights of all links connecting researchers from A to researchers from B in the co-authorship network.

For example, the departmental collaboration network of the institution shown in Figure 1 consists of three nodes P, Q and R and two links: the link connecting P and Q and the link connecting Q and R. The weight of both links is equal to 9.

In our methodological framework, the comparison of two independent groups of nodes/links in the network is based on the application of the Mann-Whitney U test (Mann and Whitney, 1947) and accompanying probabilities of superiority (Erceg-Hurn and Mirosevich, 2008). The MWU test belongs to the class of non-parametric statistical procedures which means that it does not assume any particular distribution of compared samples. Let M be an arbitrarily selected node/link metric (a metric of researcher productivity, collaboration or institutional importance in case of nodes; a metric of collaboration strength, timespan or institutional importance in case of links), and let G_1 and G_2 be the sets of M values for two independent groups of nodes/links. The MWU test is a test of stochastic superiority, and consequently it can be used to check the null hypothesis that the values in G_1 do not tend to be systematically greater or smaller than the values in G_2. The test is based on the U statistic which is the number of times a value from G_2 precedes a value from G_1 in the ranked sequence of values from both groups. Under the null hypothesis U closely follows a normal distribution. We use the MWU to examine differences between:

- intra-department and inter-department collaboration links,
- researchers involved in inter-department collaborations and researchers who do not collaborate with researchers from other departments, and
- researchers from two different departments.

For the comparison of more than two departments we rely on the Kruskal-Wallis ANOVA test (Kruskal and Wallis, 1952) which is a generalization of the MWU for more than two samples. For each conducted MWU test we record two probabilities of superiority to quantify effect size:

- $PS_1 = P(g_1 > g_2)$, where g_1 and g_2 are randomly selected values from G_1 and G_2, respectively, and $P(g_1 > g_2)$ denotes the probability that g_1 is strictly larger than g_2, and,
- $PS_2 = P(g_2 > g_1)$.

Obviously, $PS_1 + PS_2 = 1 - P(g_1 = g_2)$, where $P(g_1 = g_2)$ denotes the probability that g_1 is equal to g_2. The probabilities of superiority indicate the degree of stochastic dominance of one group over another and they can be computed in a straightforward manner (by comparing each value from G_1 to each value from G_2).

3 Researcher evaluation metrics

As emphasized in the previous Section, each researcher in a co-authorship network can be characterized by several metrics. Table 1 shows the list of researcher evaluation metrics used in our case study.

Table 1 The summary of metrics used for the evaluation of researchers (nodes in the FS-UNS co-authorship network).

Metric	Abbrev.	Metric category
Serbian Research Competency Index	SRCI	Productivity
Productivity, normal count	PRON	Productivity
Productivity, fractional count	PROF	Productivity
Productivity, straight count	PROS	Productivity
Degree centrality	LCOLL	Collaboration
The number of external co-authors	ECOLL	Collaboration
The total number of co-authors	COLL	Collaboration
Betweenness centrality	BET	Institutional importance

The first productivity metric shown in Table 1 is based on the evaluation of scientific papers by the rule book prescribed by the Serbian Ministry of Education, Science and Technological Development. The main idea of the rule book is that publication venues indicate scientific importance of publications. The rule book defines several categories of publication venues. Each category corresponds to a certain number of points that are assigned to publications according to their venues. For example,

- papers published in the top 30% SCI ranked journals in appropriate scientific discipline are worth 8 points,
- papers published in journals that are between the top 30% and top 50% SCI ranked journals are worth 5 points,
- papers published in journals with impact factor that are not among the first 50% SCI ranked journals are worth 3 points, while
- papers published in proceedings of international conferences give their authors 1 point per paper.

The Serbian research competency index for a Serbian researcher is then defined as the sum of points of publications he/she (co)authored. This metric is officially used as one of the criteria in the process of academic promotions at Serbian universities and national research centers, as well as in researcher evaluation within Serbian national research projects. To evaluate the productivity of researchers we also rely on standard productivity measures: normal count, fractional (adjusted) count, and straight count (Lindsey, 1980). Normal count gives every author of a publication one point, straight count assigns all the credit to the first author only, while fractional count assigns credit equal to $1/n$ to each of the n co-authors.

To measure the degree of research collaboration at the individual level we use three metrics:

1. Degree centrality (LCOLL) which is a domain-independent local centrality measure equal to the number of links incident to a node in the co-authorship network. This measure is equivalent to the number of local (intra-institutional) co-authors and reflects the degree of researcher's intra-institutional collaboration.
2. The number of external co-authors (ECOLL) which reflects the degree of researcher's inter-institutional collaboration.
3. The total number of co-authors which is the sum of LCOLL and ECOLL.

The institutional importance of researchers considering the underlying social structure of intra-institutional research collaboration can be measured by domain-independent global centrality metrics. In this study we rely on the betweenness centrality measure (Freeman, 1977; Kósa et al, 2015). The main intuition behind the measure is that a node in the network can be considered important if it is located on a large number of shortest paths between randomly selected nodes. This means that nodes having high betweenness are in the position to maintain and control the spread of information across the network. The betweenness centrality of a node z is computed by the following formula

$$\mathrm{BET}(z) = \sum_{x,y \in V, x \neq y \neq z} \frac{\sigma(x,y,z)}{\sigma(x,y)},$$

where V is the set of nodes in the network, $\sigma(x,y)$ is the total number of shortest paths connecting x and y, and $\sigma(x,y,z)$ is the total number of shortest paths connecting x and y that pass through z. If a network has a clustered or community organization then nodes with high betweenness tend to be located at the intersections of clusters, which means that they play the role of brokers which connect together various different parts of the network. On the other hand, nodes with low betweenness centrality are typically located on the periphery of the network. Betweenness centrality can also be used to quantify the importance of links in the network. The betweenness centrality of link l is the fraction of shortest paths between randomly selected nodes that pass through l.

4 Case study

The Faculty of Sciences in Novi Sad (FS-UNS) is an educational and scientific institution established in 1969. FS-UNS is the second largest of four public faculties of sciences in Serbia, a relatively small European country (approximately 7 million inhabitants) located at the crossroads between Central and Southeast Europe. The faculty consists of five research departments listed in Table 2.

The main goal of our case study is to investigate how institutional organization affects intra-institutional research collaboration using the methodology proposed in this paper. It can be observed that the institutional organization of FS-UNS directly corresponds to general scientific disciplines. Therefore, the analysis of research collaboration at FS-UNS can also indicate collaboration patterns characteristic for fundamental scientific fields.

Table 2 Research departments at FS-UNS.

Department	Abbrv.
Department of Biology and Ecology	DBE
Department of Physics	DP
Department of Geography, Tourism and Hotel Management	DG
Department of Chemistry, Biochemistry and Environmental Protection	DC
Department of Mathematics and Informatics	DMI

The co-authorship network of researchers currently employed at FS-UNS was constructed from the author and publication records contained in the institutional research information system called CRIS-UNS (Ivanović et al, 2010). CRIS-UNS was developed following the recommendations of the non-profit organization euroCRIS [2]. Each researcher employed at FS-UNS is institutionally obligated to have his/her CRIS-UNS record that contains all institutionally relevant data (academic rank, research department within the institution, gender, the year of birth, etc.), and periodically update (at least once at the end of a year) his/her references. Therefore, the system practically contains the complete research output of all researchers currently employed at FS-UNS [3]. CRIS-UNS is an author-article-centered bibliography database. This means that researchers registered in the CRIS-UNS system have unique identifiers which appear in the CRIS-UNS publication records. When adding a new publication, a researcher has to select co-authors among the researchers registered in the system. Also, he/she can create a profile for an external co-author (researcher not affiliated to FS-UNS) if the external co-author is not registered in the system. Therefore, each publication recorded by one author is automatically associated to all other co-authors.

Each publication record in the CRIS-UNS database contains the following information: an unique publication identifier, the complete list of author identifiers, publication year, title, publication type, and information about publication venue. CRIS-UNS supports the evaluation of publications according to the rule book prescribed by the Serbian Ministry of Education, Science and Technological Development (Ivanović et al, 2011; Ivanović et al, 2012).

[2] http://www.eurocris.org/

[3] It is important to emphasize that the mobility of Serbian researchers working at public Serbian faculties is at a very low level: almost complete scientific output of currently employed FS-UNS researchers is produced at FS-UNS.

These evauations are also stored in publication records and used to compute the Serbian research comptency index for individual researchers.

The extraction of the co-authorship network from CRIS-UNS data is a straightforward task since authors are uniquely identified in publication records, and consequently there are no name disambiguation problems. The FS-UNS co-authorship network was constructed from 14986 publications authored by 423 FS-UNS researchers and their 5690 external co-authors. The distribution of researchers per research departments is given in Table 3. To assign link weights we used the weighting scheme proposed by Newman (2004b). Namely, two researchers A and B are connected by a link of weight w computed by the following formula:

$$w = \sum_{k \in J} \frac{1}{n_k - 1},$$

where J is the set of papers jointly authored by A and B, and n_k is the number of authors of paper k. The main property of the Newman scheme is that it does not ignore the total number of authors in multi-authored publications: each joint publication of A and B adds some weight to the overall strength of collaboration between them, but the more authors a joint publication has the less weight is added.

Table 3 The distribution of researchers per research departments.

Department	Researchers	Male [%]	Female [%]	Avg. age
DMI	87	49.43	50.57	45.3
DG	66	57.58	42.42	42.9
DBE	118	25.42	74.58	41.2
DP	57	56.14	43.86	46.5
DC	95	24.21	75.79	42.7

5 Results and discussion

The FS-UNS co-authorship network contains 423 nodes (researchers currently employed at FS-UNS) and 2856 links (research collaborations). The researchers from FS-UNS have collaborated with 5690 different researchers not affiliated to FS-UNS with whom they established 34007 research collaborations in total. In this Section we present the results of the analysis of the FS-UNS network following the methodological framework described in Section 2.

5.1 Connected component analysis

Using the BFS graph traversal algorithm we identified connected components in the network. The network consists of 15 connected components where 14 of them are isolated nodes (FS-UNS researchers whose entire production consists of solo-authored publications). This means that the network possesses a giant connected component encompassing a strong majority of FS-UNS employees (96.69% of them). The existence of the giant component implies that

1. the FS-UNS researchers form a strongly cohesive institutional community of researchers, and,
2. the scientific output of the institution is not a product of many research groups that do not collaborate among themselves.

The giant connected component exhibits small shortest path lengths (the average distance between two randomly selected nodes is 3.32), and a drastically larger clustering coefficient than the clustering coefficient of comparable Erdős-Renyi random graphs. The clustering coefficient of a random graph with $N = 409$ nodes and $L = 2856$ links is equal to $2L/N(N-1) = 0.034$, while the clustering coefficient of the giant connected component of the FS-UNS network is equal to 0.566. Therefore, we can conclude that the FS-UNS network exhibits the Watts-Strogatz small-world property (Watts and Strogatz, 1998; Newman, 2001b). The Newman index of degree assortativity (Newman, 2002) is equal to 0.24 implying that highly intra-collaborative researchers moderately tend to be directly connected among themselves.

5.2 Cohesiveness of research departments

The FS-UNS network can be partitioned according to the organizational structure of the faculty into sub-networks that contain researchers belonging to the same research department. By investigating characteristics of these sub-networks we can derive conclusions related to the collaborative cohesiveness of research departments. Therefore, for each departmental sub-network we performed connected component analysis and computed graph clustering evaluation metrics quantifying group cohesion. The results are summarized in Table 4. We can see that the following holds for each of the departments:

1. The corresponding departmental sub-network has a giant connected component encompassing all researchers from the department except a small number of isolated nodes. The FS-UNS co-authorship network contains 14 isolated nodes, while there are 19 isolated nodes in the departmental sub-networks. Therefore, 5 FS-UNS researchers (1.22%) involved in inter-department collaborations have never collaborated with researchers from their own departments.
2. The total number of intra-department links is higher than the total number of inter-department links.
3. The total weight of intra-department links is drastically higher than the total weight of inter-department links implying that the departments are Radicchi weak communities (moderately strong clusters in the network). In other words, for each department we have that the total strength of research collaboration within the department is higher than the total strength of research collaborations with other departments.

Table 4 Cohesiveness of FS-UNS research departments.

Metric	DBE	DP	DC	DMI	DG
The number of researchers	118	57	95	87	66
The number of non-trivial components	1	1	1	1	1
The number of isolated nodes	3	3	0	7	6
The number of intra-department links	660	240	617	197	560
The number of inter-department links	412	174	411	71	96
Internal density	0.096	0.15	0.14	0.05	0.26
Total weight of intra-department links	8073	5636	9261	1532	2513
Total weight of inter-department links	1607	683	1825	195	160
Average internal degree	11.19	8.42	12.99	4.53	16.97
Average internal weighted degree	136.83	197.76	194.97	35.22	76.15
Weighted conductance	0.09	0.06	0.09	0.06	0.03
Weighted Flake degree fraction	0.97	0.93	0.99	0.95	0.95

The obtained values of the weighted Flake degree fraction indicate that all departments are very close to being Radicchi strong communities. Namely, a large majority of FS-UNS researchers have established stronger collaborations within their own departments than with researchers from other departments. However, in each department there is a small number of researchers (from 1 to 4) which have collaborated stronger with colleagues from other departments than with colleagues from the department they institutionally belong. In the case of institutions such as faculty of sciences, the identification of such "out-of-group" researchers is especially important since they have proven that they possess skills and knowledge highly valuable for interdisciplinary research. For example, four "out-of-group" researchers from the department of mathematics are experts in statistical modeling, discrete mathematics and partial differential equations applicable in biology, chemistry and physics.

From the data presented in Table 4 we can also observe differences between the departments. Namely, we can see that the department of geography is the most cohesive and the most closed research division since it has the highest internal density of intra-department links (and consequently the highest average internal degree) and at the same time the lowest weighted conductance. In other words, researchers from this department tend mostly to collaborate among themselves, while collaborations with researchers from other departments are relatively rare compared to other FS-UNS departments. For example, the department of physics possessing a smaller number of researchers has a drastically higher (almost two times higher) degree of inter-department collaboration. The department of mathematics and informatics possesses the weakest degree of internal cohesion. This fact can be explained by a global trend of relatively low collaboration in mathematics compared to other natural and experimental sciences (Grossman, 2002; Barabasi et al, 2002). The strongest intra-department collaboration can be observed for the department of physics and the department of chemistry whose average internal weighted degrees are significantly higher compared to other departments.

5.3 Inter-department collaborations

The FS-UNS network contains 582 inter-department links (20.4% of the total number of links in the network). Table 5 shows the results of the Mann-Whitney U test for the differences between intra-department and inter-department links. It can be seen that:

1. Intra-department collaborations have significantly higher weight and timespan compared to inter-department collaborations. This means that intra-department collaborations tend to be significantly stronger and longer in time than inter-department collaborations.
2. On the other hand, inter-department collaborations tend to have significantly higher betweenness centrality implying that they are more important for the overall cohesiveness and connectedness of the underlying social structure of the institution.

Table 5 The results of the comparison between intra-department and inter-department links. W – link weight, T – link timespan, B – betweenness centrality, U – the Mann-Whitney U statistic, p – the $p-$value of the MWU test statistic. Avg(intra) is the average value of the corresponding link metric for intra-department links, while Avg(inter) denotes the average value for inter-department links. PS_1 denotes the probability of superiority of intra-department over inter-department links, while PS_2 denotes the probability of superiority of inter-department over intra-department links. The asterisk symbol indicates the presence of statistically significant differences ($p < 0.05$) between intra-department and inter-department links.

Link metric	Avg(intra)	Avg(inter)	U	p	PS_1	PS_2
W	3.1209	0.8218	431582.5	1.77E-38*	0.663	0.3152
T	5.2093	3.299	493266	4.96E-23*	0.5025	0.2479
B	79.8237	164.7044	379504	6.39E-57*	0.2867	0.7132

Further, we divided the nodes of the network into two groups:

1. G_1 that contains researchers involved in inter-department collaborations. A researcher belong to this category if he/she co-authored at least one paper with a researcher belonging to different department, and
2. G_2 that contains researchers who have never collaborated with colleagues from other departments.

G_1 encompasses 227 FS-UNS researchers (53.7%), while the rest of them belong to G_2. We applied the Mann-Whitney U test in order to identify differences between those two groups of researchers. The results are summarized in Table 6. It can be seen that the null hypothesis of the test is rejected for each considered metric. Moreover, researchers belonging to G_1 tend to have drastically (Avg(G_1) $\gg$ Avg(G_2)) and systematically ($PS_1 \gg PS_2$) higher values of all considered researcher evaluation metrics. Therefore, we can conclude that researchers involved in inter-department collaborations tend to be drastically more productive (by all considered productivity metrics), collaborative (both locally and externally) and institutionally important than researchers who only collaborate with colleagues from their own departments. Since the FS-UNS network exhibits an assortative degree mixing pattern and the researchers from G_1 tend to have systematically higher degree centrality (the LCOLL metric in Table 6), we can also conclude that the FS-UNS network has a core-periphery structure where the researchers from G_1 constitute the core of the network.

Table 6 The results of the comparison between researchers involved in inter-department collaborations (G_1) and researchers not involved in inter-department collaborations (G_2). PS_1 denotes the probability of superiority of G_1 over G_2, while PS_2 denotes the opposite probability of superiority. The asterisk symbol indicates the presence of statistically significant differences ($p < 0.05$) between G_1 and G_2.

Node metric	Avg(G_1)	Avg(G_2)	U	p	PS_1	PS_2
SRCI	160.378	58.6939	11178.5	1.08E-18*	0.7482	0.2507
PRON	104.9031	32.9031	10333	2.06E-21*	0.764	0.2285
PROS	29.2555	13	13781	1.40E-11*	0.6764	0.2959
PROF	27.9682	12.3087	13477.5	2.69E-12*	0.697	0.3029
LCOLL	18.7225	7.4592	7486.5	4.92E-32*	0.82	0.1566
ECOLL	51.0088	13.4745	8411.5	2.52E-28*	0.8038	0.1819
COLL	69.7313	20.9337	7360	1.62E-32*	0.8304	0.1612
BET	769.6687	98.0929	7775	5.09E-31*	0.8166	0.1661

The departmental collaboration network of FS-UNS is shown in Figure 2. The widths of links in the figure are proportional to their weights, while the numeric link labels show the number of links between researchers in the FS-UNS co-authorship network. It can be seen that the departmental collaboration network is a fully connected graph which means that each department maintains research collaboration with all other departments. However, the strength of departmental collaboration links is highly unbalanced. It can be observed that the strongest departmental collaboration is between the department of chemistry and the department of biology – 150 different co-authorship links connect researchers from those two departments. The total strength of collaboration between those two departments is equal to 132,56 and it is more than four times higher than the second most strongest departmental collaboration (the collaboration between the department of chemistry and the department of physics). The weakest strength of collaboration is between the department of chemistry and the department of geography (5 links in the FS-UNS co-authorship network whose total weight is 1.09). It can be noticed from Figure 2 that several departmental collaborations have very weak intensity suggesting that there is a lot space for the improvement of inter-departmental cooperation at FS-UNS.

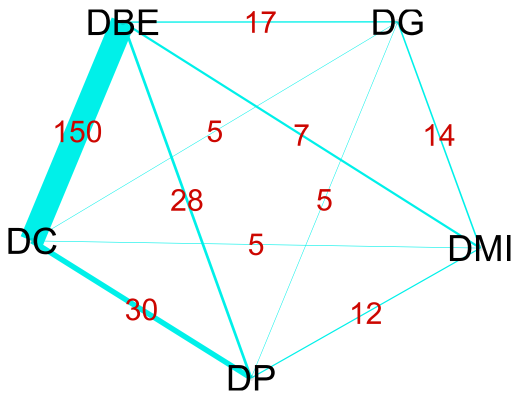

Fig. 2 The departmental research collaboration network of FS-UNS.

5.4 Evaluation of researchers

For each of researcher evaluation metrics listed in Table 1 we computed the distribution of metric values considering all nodes in the FS-UNS network. The summary of descriptive statistics of the distributions is given in Table 7. It can be seen that all distributions are highly skewed to the right (skewness > 1). The high skewness of the distributions implies that there are deep inequalities in productivity, collaborative behavior and institutional importance of FS-UNS researchers. In other words, there are FS-UNS researchers whose degrees of productivity, collaboration and institutional importance are much higher than the average values. For example, the productivity of FS-UNS researchers measured by the normal counting scheme follows the famous Pareto principle: 80% of the complete FS-UNS scientific production is authored by 20% of FS-UNS researchers (see Figure 3).

Table 7 Descriptive statistics of the distributions of researcher evaluation metrics for FS-UNS researchers.

Metric	Mean	Standard deviation	Skewness	Max.
SRCI	113.26	142.7	2.76	1124.70
PRON	71.54	95.9	3.27	871
PROS	21.72	29.9	2.92	242
PROF	20.71	28.76	3.4	266
LCOLL	13.50	10.91	1.11	56
ECOLL	33.62	40.94	2.23	260
COLL	47.12	49.17	1.98	311
BET	458.49	913.17	3.98	9064.98

The differences in productivity, collaboration and institutional importance between researchers from different departments are analyzed using the Kruskal-Wallis ANOVA test. The results are summarized in Table 8 which also shows

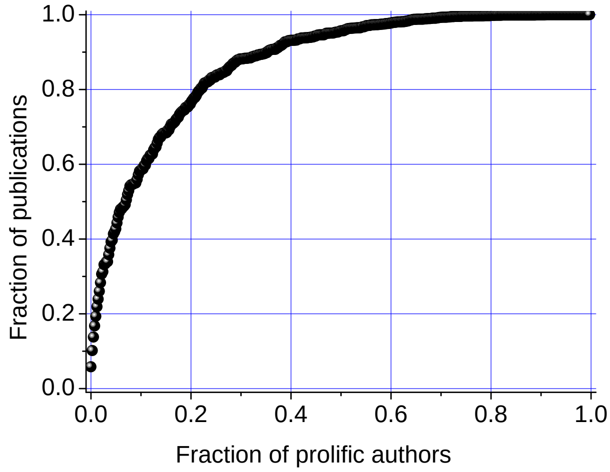

Fig. 3 The Lorenz curve showing the fraction of papers written by the most prolific FS-UNS researchers.

the average value of each metric for each FS-UNS department. From the presented data we can infer the following:

- There are statistically significant differences between researchers from different departments considering their productivity estimated by the Serbian research competency index and the normal counting scheme, but significant differences are absent when fractional and straight counting schemes are used to measure research productivity. The highest average productivity measured by SRCI and PRO has the department of physics, while the lowest values are associated with the department of mathematics and informatics. The absence of statistically significant differences in productivity measured by fractional and straight counting schemes between researchers from different departments indicates that SRCI and PRON are biased measures of research productivity.
- There are statistically significant differences in the degree of both intra-institutional and inter-institutional collaboration of researchers from different departments. The highest average degree of intra-institutional research collaboration exhibits the department of geography, while the highest average degree of inter-institutional collaboration is associated with the department of chemistry.
- There are not statistically significant differences in the institutional importance of researchers from different departments when the institutional importance is estimated by the betweenness centrality metric.

In order to detect which departments are stochastically superior considering SRCI, PRON, LCOLL and ECOLL metrics we performed a series of pairwise department comparisons relying on the Mann-Whitney U test. The results are summarized in Table 9 which shows pairs of departments for which the null

Table 8 The average values of researcher metrics per department and the results of the Kruskal-Wallis ANOVA tests. The asterisk symbol indicates the presence of statistically significant differences between departments.

Metric	DBE	DP	DC	DMI	DG	χ^2	p-value
SRCI	91.86	174.58	151.84	94.96	67.17	26.01	3.15E-05*
PRON	74.77	98.37	90.54	44.75	50.58	22.68	1.47E-04*
PROS	19.74	25.68	23.48	21.3	19.88	7.85	0.097
PROF	19.17	23.48	20.69	22.2	19.15	6.38	0.172
LCOLL	14.68	11.47	17.32	5.34	18.42	99.11	1.52E-20*
ECOLL	39.17	41.65	43.59	12.36	30.42	49.11	5.54E-10*
COLL	53.85	53.12	60.91	17.7	48.85	69.71	2.61E-14*
BET	514.21	464.53	362.39	553.4	366.87	3.24	0.51811

hypothesis of the MWU test is rejected. We can observe that researchers from the department of physics and department of chemistry have systematically higher values of the Serbian research competency index than researchers from all other departments. Namely, the probability that a randomly selected FS-UNS physicist or chemist has strictly higher SRCI than a randomly selected FS-UNS mathematician, biologist or geographer is almost two times higher than the inverse probability of superiority. Regarding productivity estimated by the normal counting scheme, it can be seen that (1) FS-UNS mathematicians have significantly lower productivity compared to FS-UNS physicists and FS-UNS chemists, and (2) FS-UNS chemists have significantly higher productivity than FS-UNS biologists and geographers. Since there are no statistically significant differences between FS-UNS departments considering productivity estimated using fractional and straight counting schemes, we can conclude that SRCI and PRON are biased towards FS-UNS physicists and chemists. Therefore, those two productivity metrics cannot be used to compare productivity of FS-UNS researchers from different departments. This is especially important since SRCI is officially used in the process of academic promotion, but also in many official, administrative decisions (e.g. SRCI is used by the UNS housing commission as one of factors when forming priority lists for flat allocation, and by the Ministry of Science when approving and evaluating national research projects).

From the data presented in Table 9, it is evident that the organizational structure of FS-UNS has a strong impact on both intra-institutional and inter-institutional research collaboration. We can see that the researchers from the department of mathematics and informatics have drastically lower degree of both intra-institutional and inter-institutional collaboration compared to researchers from other departments. On the other hand, the researchers from the department of geography and the department of chemistry have significantly higher degree of intra-institutional collaboration than researchers from other departments, and at the same time statistically significant differences in the degree of inter-institutional collaboration are absent. Therefore, we can conclude that those two departments actively stimulate intra-institutional research collaboration.

Table 9 The results of pairwise comparison of FS-UNS departments for which statistically significant differences in researcher evaluation metrics are present. PS_1 denotes the probability of superiority of Department 1 over Department 2, while PS_2 is the inverse probability.

Metric	Department 1	Department 2	U	p-value	PS_1	PS_2
SRCI	DG	DP	1280	0.0023	0.34	0.66
	DBE	DP	2516.5	0.0071	0.37	0.62
	DP	DMI	1825.5	0.0076	0.63	0.37
	DG	DC	1956	0.0001	0.31	0.69
	DBE	DC	4046.5	0.0005	0.36	0.64
	DMI	DC	2884	0.0004	0.35	0.65
PRON	DP	DMI	1824.5	0.0075	0.63	0.36
	DG	DC	2236.5	0.002	0.35	0.64
	DBE	DC	4345	0.0048	0.38	0.61
	DMI	DC	2481	$< 10^{-4}$	0.29	0.69
LCOLL	DG	DBE	2913	0.0046	0.62	0.36
	DG	DP	1094.5	0.0001	0.70	0.28
	DG	DMI	851	$< 10^{-4}$	0.84	0.14
	DBE	DMI	2297.5	$< 10^{-4}$	0.75	0.20
	DP	DMI	1150.5	$< 10^{-4}$	0.75	0.21
	DBE	DC	4521	0.0153	0.39	0.58
	DP	DC	1888.5	0.0018	0.33	0.63
	DMI	DC	1073	$< 10^{-4}$	0.12	0.86
ECOLL	DG	DMI	1576	$< 10^{-4}$	0.71	0.26
	DBE	DMI	2906	$< 10^{-4}$	0.70	0.27
	DP	DMI	1319	$< 10^{-4}$	0.72	0.25
	DMI	DC	1879	$< 10^{-4}$	0.22	0.76

6 Conclusions

Current research information systems (CRISs) offer great possibilities to analyze research output and collaboration at the intra-institutional level. However, these possibilities have been rarely exploited in contemporary scientometrics studies. We proposed the hybrid methodology to analyze enriched intra-institutional co-authorship networks constructed from CRIS databases. Our methodology is based on:

- connected components analysis and graph clustering evaluation metrics in order to investigate the cohesiveness of intra-institutional research collaboration at the level of the whole institution and the level of departments within the institution,
- the structural analysis of departmental collaboration networks induced from intra-institutional co-authorship networks in order to reveal patterns of collaboration between research departments, and
- non-parametric statistical procedures applied to independent groups of nodes/links in the network in order to (1) evaluate the differences between researchers from different departments with respect to their productivity, collaborative behavior and institutional importance, and (2) determine characteristics of researchers involved in inter-department collaborations.

Using the proposed methodology, we analyzed the intra-institutional coauthorship network extracted from the institutional CRIS system of the Faculty of Sciences, University of Novi Sad (FS-UNS). The connected component analysis revealed that FS-UNS is an institutionally cohesive research community with a very small fraction of researchers whose research output entirely consists of single authored publications. The analysis of departmental cohesion based on graph clustering evaluation metrics indicated that a very large majority of FS-UNS researchers have established stronger collaborations within their own departments than with researchers who institutionally belong to other departments. However, researchers involved in inter-department collaborations tend to be drastically more productive, both locally and externally collaborative, and institutionally important compared to colleagues whose collaboration is bounded to their own research departments.

Empirically observed distributions of researcher evaluation metrics are highly skewed to the right implying that there are deep inequalities regarding the productivity, collaboration and institutional importance of FS-UNS researchers. Further analysis based on non-parametric statistical tests revealed that there are statistically significant differences in the productivity and collaboration of researchers from different departments, but not regarding their institutional importance. Two FS-UNS departments have significantly higher degree of intra-institutional research collaboration compared to the rest of FS-UNS departments indicating that those two departments actively stimulate intra-institutional research collaboration. Finally, we observed that statistically significant differences in the productivity of researchers from different departments are present when research productivity is estimated using the normal counting scheme and the Serbian research competency index, but absent when research productivity is measured by the fractional or straight counting scheme. Therefore, we can conclude that the Serbian research competency index is not an adequate measure to compare researchers from different scientific disciplines, and it should be avoided in strategic and administrative decision making.

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